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Further reflections on the temporality of energy transitions: A response to critics

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Abstract: In tandem with the call for more careful, thoughtful, reflexive thinking on the topic of energy transitions, in this paper we attempt to unpack some of the themes advanced in this Debate. We begin by investigating the multi-dimensionality of energy transitions as well as transition speeds for different parts of energy systems at different scales. We then call on analysts to consider transition speeds and scalar levels. We also argue for focusing on accelerated diffusion driven by rapid changes in cost, improvements in technology, or other factors.

Keywords: sociotechnical transitions; energy transitions; energy transformation; energy substitution

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Introduction

Sarrica et al. (2016) have advanced our understanding of energy transitions across individual, community, national, and even theoretical planes, and Sovacool (2016) has attempted to facilitate a critical albeit reflexive and productive discussion about the timing and temporal dynamics of energy transitions. Messengers Grubler et al. (2016), Smil (2016), Kern and Rogge (2016), Fouquet (2016) and Bromley (2016) rightfully build and challenge some of the arguments presented in the special issue on energy transitions this journal published a few months ago.

However, when Grubler et al. (2016) argue that "Sovacool's strawman comparison between the slow dynamics of global primary energy transitions and the seemingly rapid dynamics of national end-use and resource transitions fail to account for any of these important determinants" and Smil (2016) adds that "[Sovacool's] wishful thinking is contradicted both by indisputable statistics and by the imperatives of energy conversions," a partial defense is in order. The central argument advanced in Sovacool (2016) was not that quick transitions determinedly happen, but that there are two almost mutually exclusive academic discussions on the topic, one of them aligned with Grubler, Smil and others about the lengthiness of transitions; and another with separate scholars arguing in favor of speed (with Bromley 2016, Kern and Rogge 2016, and even Fouquet 2016 furthering some of these claims in their new contributions). In the extreme, one could even criticize this academic dichotomy as "hard historical facts" versus "normative, future-orientated desires."

We suggest, however, that these two tracks represent a deeper difference between techno-economic analysis (focused on 'tangible' elements) and socio-institutional analysis (focused also on 'intangible' elements and actors) with important implications for differences between historical and future transitions, which we discuss below. The "How Long Will it Take?" article was an attempt to draw attention to these tensions: it was not meant to present one side as determinable truth, only that the answer to the question will depend on fundamental definitions and assumptions—what some recent work has called intellectual, cognitive, or epistemic frames (Haas 1992; Knorr-Cetina 1999; Sovacool and Brown 2015; Sovacool et al. 2016)—that are not always as transparent or apparent as they need to be. In that regard, despite perhaps misrepresenting the central purpose of that article, the six pieces here in this special "Debate" in the journal are apt and insightful; the advancing intellectual dialogue hoped for has been accomplished.

In line with the need for more careful, thoughtful, reflexive thinking on the topic of transitions, in this paper we attempt to unpack some of the themes advanced in this Debate. We begin by investigating the multi-dimensionality of transitions as well as transition speeds for different parts of energy systems at different scales.

Multi-dimensionality of transitions

Geels and Schot (2010: 12) note that "transitions are co-evolution processes that require multiple changes in sociotechnical systems or configurations" and that these can involve "development of technical innovations (generation of novelties through new knowledge, science, artifacts, and industries) and their use (selection, adoption) in societal application domains." Transitions also include regulations, markets, infrastructures and cultural symbols. Therefore, transitions are multi-actor processes, involving interactions between firms, households, policymakers, social movements, scientific communities and special interest groups. They are radial shifts from one system to another and such radicalism can be understood not only as shifts in time but also as shifts in scope: radical innovations can be disruptive and also lead to Schumpeter's "creative destruction."

Geels (2004), more analytically, suggested that transitions involve changes in three interrelated dimensions: 1) the tangible elements of socio-technical systems (technologies, markets, consumption patterns, infrastructures, production facilities, supply and distribution chains), 2) actors and social networks (new strategies, investment patterns, change coalitions, capabilities), 3) socio-technical regimes (formal rules and intangible institutions like norms, mind-sets, belief systems, discourses, views on normality, social practices). So, the two tracks noted above partly stems from scholars focusing on different dimensions of a complex phenomenon. Grubler et al., Fouquet, and Smil focus on tangible elements and a sub-set of actors (mainly firms and consumers), whereas Kern and Rogge and Bromley (and Fouquet to some extent) focus on a wider set of actors and changes in institutions and regimes, which may shape identities, preferences and interpretations of actors, as well as markets.

This distinction also helps explain their different views on the temporality of transitions. Grubler et al and Smil see transitions as slow because of various techno-economic rationales: 1) it takes a long time to build large (infrastructural) systems, 2) new technologies and systems only gradually improve their competitiveness (via learning curves and scale economies), which leads to gradual replacement of incumbent systems in existing markets, 3) existing technologies and systems will disappear slowly, because of sunk investments and economic logics to milk assets until they are written off. Kern and Rogge and Bromley see low-carbon transitions as potentially faster than historical transitions, because political will and a societal sense of urgency may lead to policies that change markets and selection environments (e.g. carbon tax, cap-and-trade, feed-in-tariffs, renewables obligations, contracts-for-difference) or even phase-out technologies before they are written off (e.g. the German nuclear phase-out, ban on incandescent light bulbs, plans to phase-out coal). So, the core of their argument is that politics may trump economics, particularly if supported by wider publics, a sense of urgency about problems, and cultural discourses that frame existing technologies as undesirable or dangerous and low-carbon technologies as creating jobs, improving quality of life or protecting nature.

The distinctions are also important to reflect on the implications for future low-carbon transitions, which was Sovacool's background motivation. Arguably, there are two important differences between historical and future low-carbon transitions. First, historical transitions were more 'opportunity' driven, whereas low-carbon transitions are more 'problem-driven'. Since this problem involves a collective good (the climate), policymakers and civil society will have to play important role to overcome free rider problems and internalize negative externalities. Second, in evolutionary terms, historical transitions were more about developing 'variations' (technologies), whereas low-carbon transitions will also be about adjusting 'selection environments' (via policies, regulations, incentives that shape markets). Both differences imply that socio-institutional processes will be crucial in low-carbon transitions besides techno-economic dimensions. Grubler et al and Smil insufficiently recognize these differences, which limits the generalizability of their historical findings. We therefore concur with Kern and Rogge (2016), who write that "while history is important in order to understand the dynamics of transitions, the pace of historic transitions is only partly a good guide to the future." They also note that dynamic feedback mechanisms may be different going forward and that the sheer urgency and wicked nature of climate change as a global problem may motivate action. The old adage "necessity is the mother of invention" comes to mind.

Transition speed and different (layers of) energy systems

With regard to tangible elements of energy systems, it may be useful to distinguish different 'parts' or 'layers' and investigate the implications for transition speed. We suggest that one can break down transitions into subsystems across at least four layers.

1. The *extractive industries* most related to energy production encompass the mining of coal and the production of crude oil and natural gas, as well as (occasionally) the mining and processing of uranium. The extractive industries also provide the material needs—copper, rare earth elements, alumina, and others—needed to manufacture power plants, cars, transmission lines, and other electronic devices, something we call "critical materials." In essence, the need for all of these resources reminds us that "energy" must be mined, leached, processed, and turned into usable products that can be bought and sold.
2. *Systems of national conversion and supply* are more frequently discussed, and the articles in the Debate are no exception. These involve the networks of power plants, oil and gas refineries and petrol stations, and other infrastructures that convert extractive resources—including fossil fuels as well as alternatives—into electricity, heat, mechanical energy, or liquid fuel.
3. *Prime movers* (or end-use technologies) are "energy converters able to produce kinetic mechanical energy in forms suitable for human uses" (Smil 2010: 6). That is a fancy way of saying they are the technology that converts primary and secondary fuels into useful and usable energy services. Without prime movers, all of the dazzling technological advances human civilization has made over the past millennia would remain nothing more than unrealized concepts. Human muscles are the classic prime movers; those muscles enabled us to hunt, gather, and farm. The first mechanical prime movers were simple sails, water wheels, and windmills; the industrial revolution had its steam engines and turbines; the modern area has internal combustion engines, jet turbines, compact florescent light bulbs, and household electric appliances (Jefferson, 2015).
4. Energy resources and prime movers need *delivery infrastructure* to connect them, and while such transportation and distribution systems are breathtakingly variegated, the three most prominent are pipelines, tankers, and electric transmission and distribution lines. Taken together, this

infrastructure occupies a substantial chunk of land, with one assessment estimating that roughly 30,000 square kilometers—the size of Belgium—are currently dedicated exclusively to supporting the oil, gas, coal, and electricity industries (Smil 2010).

Now, Grubler et al (2016) and Smil (2016) suggest that the creation of new delivery infrastructure systems (e.g. electricity grids, highway systems) is almost always a slow decades-long process, because of their capital intensity, geographical spread, and complexity, something that resonates with large technical system research (Hughes, 1983; Mayntz and Hughes, 1988). We agree with this, but note there may be exceptions, where opportunities, political will and business support may accelerate dynamics. One example is the creation of a national gas infrastructure in the Netherlands (one of Sovacool's examples), where the discovery of huge natural gas reserves led a coalition of Shell, Exxon and the government to develop a national roll-out plan (Correljé and Verbong, 2004). Another example (also mentioned by Sovacool) is the creation of district heating systems in Denmark (linked to CHP), after the 1973 oil shock created a high sense of urgency because of the country's high dependence on oil.

We suggest that the creation of extractive industries and conversion systems also generally tends to be slow, because of capital intensity and complexity. Natural resource discoveries (or technical breakthroughs that enable natural resource exploitation) may, however, lead to bonanzas and rapid creations of extractive industries. Sovacool already mentioned Kuwait oil and Dutch natural gas, but the US shale gas revolution also comes to mind. Political will may also lead accelerate developments, as happened in the case of French nuclear power, where large technocratic projects were a means to re-establish national honor and prestige after military humiliations in the Second World War (Hecht, 1998); interventionist policy styles and engineering cultures further enabled these projects. Political intervention and support policies also led to rapid diffusion of renewable electricity in Germany (from

5.2% in 1999 to 30.1% of German electricity production in 2015) and the UK (from 2.5% in 2001 to 24.7% in 2015). Smil’s dismissive assessment of the German electricity transition is surprisingly partial and short-sighted. He is correct in noting the paradoxical rise of CO2 emissions since the *Energiewende* policy in 2011 (due to increased lignite and decreased gas burning), but fails to note subsequent plans to diminish coal-burning. As previous studies have shown (e.g. Geels *et al*., 2016), transitions are non-linear processes, so surprises and unintended consequences are to be expected (especially after radical decisions such as a nuclear phase-out).

Grubler et al argue that substitutions of end-use technologies can be fast, because they do not require broader system change (and the associated lengthy experimentation and learning processes). Indeed, quite a few of Sovacool’s examples relate to changes in prime movers (see Table 1). So, we agree in large part with Grubler et al.’s ‘apples and oranges’ criticism: that examples of rapid transitions in prime movers should not be generalized to transitions in infrastructural systems. Our distinction of four different layers of energy systems is an attempt to create more clarity.

Table 1: Energy System Layers and Socio-Institutional Characteristics

	‘Layer’ of energy systems	**Socio-institutional characteristics**
Swedish energy-efficient lighting	Prime mover	Small population; consensual policy style
Chinese cookstoves	Prime mover	Authoritarian state
Indonesian LPG stoves	Prime mover	
Brazilian flex fuel vehicles	Prime mover	Authoritarian state (military junta introduced biofuels)
US air conditioning	Prime mover	
Kuwait crude oil	Upstream extraction	Authoritarian state
Dutch natural gas	Upstream extraction; national systems of supply; delivery infrastructure	Small population; consensual policy style
French nuclear power	National systems of supply	Strong state intervention
Danish CHP	National systems of supply (electricity), delivery infrastructure (heat)	Small population; consensual policy style
Ontario coal (phase-out)	National systems of supply	Small population

Source: Authors’ compilation.

Nevertheless, there are examples where infrastructural, extraction and conversion systems were created or altered rapidly, and our discussion above showed that politics and institutions played crucial roles in them. There is also the ability for transitions at one discrete layer or involving one type of energy technology to compound. For instance, an improvement in resource extraction by a factor of three (say, at a shale gas site), when coupled with an improvement in energy conversion (say, at a natural gas power plant) by a factor of two, delivery efficiency (at a pipeline) by a factor of two, and end-use consumption (say at an electric refrigerator) by a factor of three, results in an overall efficiency improvement by a multitude of 36—the aggregated impact of overall improvement is greater than the sum of the parts. Changes that may appear to be slow at one isolated layer—national energy conversion and supply, for instance—become multiplicative when one takes a systemic, multilayered perspective (Cullen and Allwood 2010). In other words, four innovations that may appear discrete in within their layer result in a more radical systemic impact. Cullen et al. (2011) forcefully affirmed this point when they noted that while changes in "passive devices" could reduce global energy demand by some 73%, the amount skyrockets when you consider other elements of the system that couple with those technologies, such as "conversion devices" or "active systems." In very simple terms: what may appear as laggardly change at one layer of the system obscures the accelerated impact across the system's whole.

A further explanation of potential high transition speed in end-use technologies is the rapidity of learning rates and accelerated incremental innovation (Wilson et al. 2012). Smaller, more modular technologies can better exploit rapid learning, as many generations of product development can be compressed into the time it would take to build one giant plant (Jamasb and Kohler 2007; Christiansson 1995). As Lovins and his colleagues (2002: 252) note, "technologies that deploy like cell phones and personal computers are faster than those that build like cathedrals. Options that can be mass-produced and adopted by millions of customers will save more carbon and money sooner than those that need specialized institutions, arcane skills, and suppression of dissent." The implication for transitions is that rates of learning and innovation as well as scalability and modularity can produce technologies that can be innovated in ways that earlier systems cannot, with inherent technological characteristics predisposing them towards cumulative or accumulated breakthroughs unforeseen before they happen. This mechanism may apply to end-use technologies (e.g. LED lighting), but also to smaller or modular generation technologies (e.g. wind turbines, solar panels), where earlier techno-economic assessments have under-estimated technical progress and diffusion (Gaede and Meadowcroft, 2016; Gilbert and Sovacool, 2016).

Transition speed and scalar levels

Scale is another important dimension for the debate on transition speed. Sovacool's (2016) examples of rapid transitions all refer to countries and sectors. Both Smil (2016) and Grubler et al. (2016) agree that country-level transitions (and those in particular cities or local communities) can indeed be rapid. But they also suggest that "grand" transitions at the global scale and covering entire economies are necessarily slow and gradual, e.g. the shift from biomass to coal, the shift from coal to oil, or the transition from fossil fuel to low-carbon sources. Some of the techno-economic rationales are huge sunk investments, infrastructural inertia, technical complexity, and diversity of markets and sectoral application. We also note, however, that the gradual *global* pace results from 'averaging effects', where (rapid) sectoral developments in front-runner countries are outweighed by slow developments in countries that (very) heavily rely on fossil fuels.

We agree with the general point, however, and accept that Sovacool (2016) insufficiently clarified this scalar distinction. But we disagree with the suggestion that global "grand" transitions are only driven by techno-economic considerations, which Smil (2016) and Grubler et al (2016) seem to privilege. Instead, taking scalar thinking seriously, we suggest that global “grand” transitions unfold country by country and sector by sector, which involves concrete actors and institutions, as indicated above. Also for global transitions, it thus remains important to analyze rapid country-level transitions, because these first movers contribute to learning processes, scale economies, articulation of positive discourses, and changes in businesses strategies. The influence of Germany with regard to global solar-PV diffusion is only one case in point. Other actions below the level of the nation-state can also be important, for instance those of communities, intermediaries, and other “middle” level actors (Parag and Janda 2014) or particular points of major energy-consuming activity, such as airports, ports or harbors (Van Driel and Schot 2005).

With regard to our earlier discussion of multidimensionality, the scalar dimension has an important implication, namely that higher scales seem to privilege more abstract kinds of approaches like economics (or functionalism). In a chapter on technological determinism, the historian Tom Misa (1994: 119) diagnosed that: “macro studies tend to abstract from individual case studies, to impute rationality on actor’s behalf or posit functionality for their actions, and to be order driven. (...) Micro studies tend to focus solely on case studies, to refute rationality (...) and functionality, and be disorder-respecting.” This suggestion helps explain why Grubler et al (2016) and Smil’s (2016) discussion of *global* transitions seems to prioritize techno-economic considerations. This is, however, mainly a methodological and epistemic construct, and we warn against drawing the conclusion that economics is the main or only driver of global transitions (as often happens in global climate models).

To overcome his noted dichotomy, Misa (1994: 140) makes a plea for "a focus on meso-level institutions and organisations that mediate between the individual and the cosmos”. Such analyses of concrete institutions and societal groups can be done at the country- and sector-level, which thus form an important *complement* to aggregate global studies. We do not mean to privilege either techno-economic or socio-institutional analyses, but suggest that both are necessary. Additionally, however, we suggest that greater reflexivity may be needed with regard to scales: different scales refer not simply to different aggregate entities, but also have epistemic implications for methods, theory and explanation (Geels *et al*., 2016).

Moreover, there is a politics to the neglect of context in macro-approaches, and a link to planning that often goes unacknowledged. Scott (1998) suggests that: “The lack of context and particularity is not an oversight; it is the necessary first premise of any large-scale planning exercise. (…) Standardized citizens are uniform in their needs and (…) have, for the purpose of the planning exercise, no gender, no tastes, no history, no values, no opinions or original ideas” (p. 346). The point here is that scales and modes of representation are not politically neutral, since they empower some perspectives and exclude others.

From transition speed and duration to acceleration

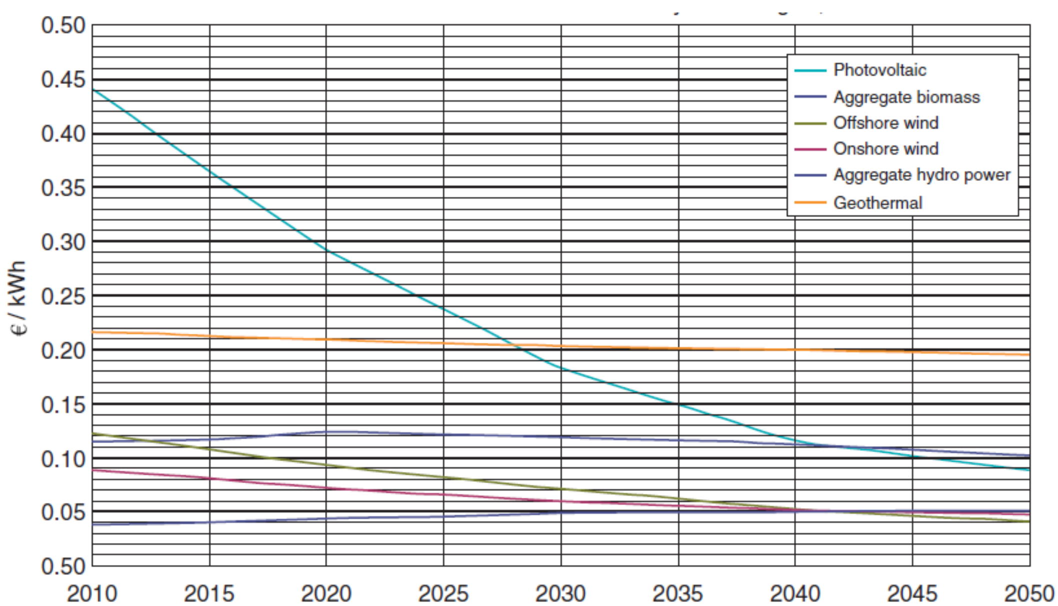
Grubler et al. (2016) make another point we concur with: they suggest that “it may be the most important contribution of Sovacool’s thought-provoking piece: to move the discussion from ‘How long does it take?’ to ‘What does it take?’ to achieve rapid transitions.” Fouquet (2016) lends support to this line of argument when he notes that “Crucially, energy transitions are non-deterministic. That is, energy transitions are not inevitable; instead, they depend on a series of actors and forces creating a new path.”

So, while the duration and measurement of historical transitions are interesting research topics, it may be of greater political relevance to investigate the acceleration of transitions. From a quantitative viewpoint, this would relate to the ‘tipping’, ‘take-off’ or ‘inflection point’ in S-shaped diffusion curves. Techno-economic explanations typically refer to ‘killer applications’ (which open up larger market niches) or ‘increasing returns to adoption’ which improve price/performance characteristics, e.g. learning by using, network externalities, scale economies in production, informational increasing, technological interrelatedness (Arthur, 1988). Socio-institutional explanations would refer more to the shifts in allegiance of social groups like policymakers or wider publics, whose defection from old to new systems may lead to major changes in policies or discourses. In political science, this is conceptualized under the heading of shifts in policy paradigms (Hall, 1993; Coleman, 1996), which refers not only to new policy instruments, but also to new policy goals and problem definitions. Organization studies highlights the importance of shifts in public discourses that can de-legitimate existing technologies or industries (Maguire and Hardy, 2009; Geels and Verhees, 2011), which in turn affect policy support and access to resources (Loundbury and Glynn, 2001). It would be interesting and highly relevant to further investigate interactions between techno-economic and socio-institutional processes in the acceleration of transitions. Our hypothesis is that socio-institutional changes prepare the ground for techno-economic tipping points and are thus likely to precede actual accelerations by several years.

Two other factors connected to but beyond climate change could further accelerate future transitions. One of them is sheer scarcity. While past transitions may have been rooted in abundance, future ones may involve scarcity. Indeed, we already have some historical examples of fast, scarcity-driven transitions. The massive energy transitions that occurred in Japan from 1918–1945, North Korea in the 1990s, and Cuba in the 1990s saw societies grapple with sudden disruptions in the availability of energy. Japan lost upwards of 70 percent of its oil imports due to the U.S. trade embargo of 1941, North Korea dropped 90 percent of their oil imports from the Soviet Union in 1991, and Cuba saw a decline of energy imports from the Soviet Union of 71 percent between 1989 and 1993. In each case, national planners never intended to initiate transitions nor did they anticipate a pending shortage of fuel (Friedrichs 2013).

The other is prices, which can also play a critical role in transitions. Both Fouquet (2016) and Bromley (2016) suggest that if one changes the price of a given technology or energy service, then one can directly influence its speed of diffusion. To be clear, we do not want to reduce a transition merely to price—to do so is to succumb to economic determinism. Prices and costs are always shaped and influenced by broader social forces including policies (taxes, subsidies, loans), but also responsibilities (e.g. for nuclear decommissioning). That said, many studies have recently painted an increasingly optimistic vista for particular low-carbon energy systems given that their prices are rapidly improving (in both a comparative and absolute sense). Solar photovoltaic (PV) module prices, for instance, dropped from more than $3 per Watt-peak (Wp) in 2008 to less than $1 per Wp in 2012. Prices are expected to fall even further as "soft costs" such as permitting and labor for installation continue to decline (Ardani and Seif 2013). Although the levelized cost of solar-PV depends increasingly on system costs (which depend on what will be decided about infrastructure connection costs) and deployment cost (which depends on supply chains, skills etc.), such reductions in cost and improvements in performance were anticipated by few, and are already having far-reaching impacts on electricity markets, especially those for peak power. Similarly, the cost of wind power, which was estimated at approximately $50-60 per MWh in 2010, is projected to decline to $35-55 per MWh in 2030 (Hearps et al. 2011). Figure 1 shows that many renewable energy costs are only set to *decline* in the future as technologies improve.

Figure 1: Expected Levelized Costs for Renewable Electricity from 2010 to 2050



Source: Hohmeyer and Bohm 2014.

Conclusion

Admittedly, Sovacool (2016) was meant to be fairly speculative and slightly provocative. It was motivated to instigate readers to ask critical questions about transitions and challenge the predominate thinking anchored in so much social science research. We wonder if the very hesitancy from us (social scientists or even researchers and analysts) to validate the notion of expedient transitions, and the continued dominance of techno-economic analyses rooted in modeling, contributes in part to the very "lock-in" or "path dependency" we critique. We endow the fossil fuel regime with perhaps more agency than it actually has or need have. Techno-economic and socio-institutional processes are both important, as are all layers of the energy system—extraction, conversion, delivery and use—at multiple scales.

At an even deeper level, the issue may relate to different ontological assumptions such as realism/positivism (which assumes that markets are objective and given) and constructivism (which assumes that markets are, at least partially, shaped). Economic sociologists, for instance, argue that governments constitute markets both in a *foundational* sense (Fligstein, 1996) by establishing property rights, rules of exchange, and governance structures (establishing legal and illegal forms of corporate behavior) and through *specific* policies like standards, loans, cash grants, tax concessions, information and research services. Lindblom (2001: p. 42), for instance, proposes that: "If the market system is a dance, the state provides the dance floor and the orchestra."

Another noted lacuna in energy transitions research is considering, as Fouquet (2016) proposes, "the inequality associated with energy transitions." Here we need to shy away from merely describing the temporal dynamics transitions to making normative claims about them based on criteria for evaluation or judgment. We could begin to think about what transitions *should* do, at what their speed ought to accomplish, or why a transition is needed, as well as who might win or lose based on it. Put another way, we need to reframe or re-politicize what fast transitions accomplish, or what slow transitions prevent from occurring. Fast or slow transitions can be mechanisms of resource extraction that transfer wealth from developing countries to developed ones, or systems of segregation that separate negative harms from the positive attributes across different classes of consumers (Sovacool 2016b). Some end-use transitions mentioned by Sovacool (2016) can even lock-in unsustainable or high consumption end-use patterns, e.g. the proliferation of lifestyles rooted in air conditioning (United States) or dependence on petroleum-fueled automobiles (Kuwait) or other forms of motorized transport

(Brazil). In more extreme situations, transitions can facilitate human rights abuses, such as natural gas pipeline revenues in Azerbaijan or Myanmar (Burma) (Sovacool 2011) or oil revenues in Nigeria (Watts 2016). Transitions can become intertwined in national discourses of revitalization or national security, such as uranium in Australia (Diesendorf 2016), or even validate distinct approaches to economic and social development such as loans for coal-fired power stations backed by the World Bank (Hunter 2003). While the importance of such issues may appear blatantly obvious to some, most assessments continue to ignore the entire range of possible impacts a given transition can have on society.

The point is that the very discourse academics use to frame and engage on a topic can distort and even reinforce aspects of that topic. The language we use to describe transitions serves as more than a mere analytical tool—it can shape how energy system users, investors, operators, builders and financiers frame energy problems and also envision future pathways for change. So far, the academic discussion about energy transitions remains mostly narrow: focused on techno-economic models, and wedded to the idea that energy transitions will invariably and inescapably take a long time. While we appreciate the evidence in support of this view, it does not adequately capture the multi-dimensionality of transitions, or that speed can agglomerate at different parts of energy system or at scalar levels. Such thinking also lacks an assessment of whether prices or changes in end user patterns may precipitate in accelerated diffusion unheard of in generations past. In other words, we need to ask not only "How long will it take?" but also "How much will it cost?", "How can layered or scalar transitions aggregate?", and "How may future innovation differ from the historical record?" And so while history, as Grubler (2012) notes, may be the "only observational space" in which transitions can be understood, that understanding can certainly be instructive, but it is not necessarily predictive.

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